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# Motion Detection in the Far Peripheral Visual Field

**by William A. Monaco, Joel T. Kalb, and Chris A. Johnson**

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# Motion Detection in the Far Peripheral Visual Field

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**14. ABSTRACT**

Our objectives were to apply Bayesian threshold estimation procedures and new technology to the determination of motion detection (angular velocity) and to determine whether threshold measures, combined with large screen technology and specialized software, could be used to evaluate human motion sensitivity in the far peripheral visual field beyond 50 degrees' radius. With the use of the Parameter Estimation by Sequential Testing threshold estimation procedure, black dot targets were presented at 53.4, 72.6, and 90 degrees' eccentricity in the temporal visual field of two subjects who had normal visual function. Motion detection thresholds demonstrated a systematic increase with increasing visual field eccentricity and could be obtained within 10 stimulus trials. The average angular velocity motion thresholds were approximately 0.5 degree per second for the 54.3-degree eccentricity, 1.2 to 1.5 degrees per second for the 72.6-degree eccentricity, and 2.1 degrees per second for the 90-degree eccentricity. Our findings indicate that it is possible to obtain motion detection (displacement) thresholds in the far peripheral visual field using Bayesian threshold estimation procedures. In view of the importance of motion detection in the periphery for stimulus localization, attentional demands, orientation and mobility tasks, this procedure may have significant applications for many military visual tasks.

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extreme retinal periphery; motion detection

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# 1. Introduction

The fovea and macular region of the visual system are primarily responsible for the human ability to appreciate spatial detail (visual acuity), discriminate color, stereopsis, and other fine discriminations, and for complex tasks such as reading and face recognition (*1* through *4*). In the peripheral visual field, the primary visual functions that are performed involve stimulus detection, flicker and motion sensitivity, and visuo-vestibular interactions (*5* through *10*). Evaluation of different visual functions in the peripheral visual field indicates that some tasks such as color discrimination and visual acuity are substantially degraded in comparison to the fovea, while others such as stimulus detection, motion and flicker detection are only modestly diminished (*6* through *8*). Peripheral visual functions such as stimulus detection, flicker sensitivity, and motion detection are important for noticing targets, localizing and orienting objects, directing eye movements toward stimuli for more detailed foveal inspection, and enhancing one's awareness of the environment. For tasks that involve the surveillance, detection, and identification of objects, as well as navigation during poor visual conditions, the ability to detect movement is critical, particularly for the far peripheral field of view. In addition, motion detection in the periphery (motion perimetry) has been found to be a valuable clinical ophthalmic tool for early detection and differential diagnosis of ocular and neurologic disorders (*11* through *17*).

Detection of motion has been a subject of investigation for many years and has been measured in terms of displacement (spatial change) thresholds (*12*, *14*, *18* through *30*), velocity or rate thresholds (*31* through *37*), motion coherence thresholds (*15* through *17*), and contrast thresholds (*38*). Each of these procedures is able to reveal different features of peripheral visual function; these procedures are affected by a number of stimulus parameters. In general, motion detection has been reported to be a robust attribute of peripheral visual function, (*15*, *23*), revealing fairly consistent threshold responses for a variety of different conditions. Evaluations of the far peripheral visual field have been reported by a number of investigators (*21*, *38*, *39*). However, most of this research has been conducted more than 20 years ago with limited field of view (FOV) because of the use of cathode ray tube (CRT) displays and computer monitors used for generating displays. The evolution and refinement of large screens and immersive environments now allow investigators to generate high resolution targets with specific color, motion, and spatial frequency attributes. Further, large screens eliminate the restricted FOV and limited testing distances imposed by smaller conventional CRTs. Moreover, threshold estimation procedures have been modified in recent years to allow accurate and efficient acquisition of measures through the use of Bayesian statistical procedures (*40* through *44*). These events have led to their joint application to the investigation of motion detection in the far peripheral visual field. In addition, a recent investigation has reported that the neural basis for motion processing in the far temporal visual field is different from other portions of the peripheral visual field, so psychophysical examination of this topic may yield new insights into the anatomical and physiological basis for these differences (*39*). Motion detection has been reported to be an important factor in the performance of real-world tasks (*45*, *46*) and in differential diagnosis of ocular and neurologic disorders (*11*, *12*, *14* through *17*, *47*). The purpose of the present investigation is to determine the feasibility of measuring motion detection for the far peripheral visual field, to evaluate the ability of Bayesian threshold estimation procedures to determine motion thresholds, and to derive a vision test methodology that could be applied to real-world task performance activities. To our knowledge, far peripheral motion detection has not been explored via the new wide-screen technology and Bayesian estimating or forecasting strategies. Most clinical procedures use measures of the near periphery (within the central 30 degrees) where a significant portion of ocular pathology is exhibited. However, this study explores the far retinal periphery where target detection and surveillance are most crucial. In summary, our investigation of motion detection in the far peripheral visual field was directed toward three objectives: (1) to examine the feasibility of measuring motion detection thresholds in the far temporal visual field beyond 50 degrees' eccentricity, (2) to determine the ability of Bayesian test strategies to measure motion thresholds for the far peripheral visual field, and (3) to develop a methodology that would permit motion threshold determinations that could be directly applied to "real-world" task performance activities.

## 2. Methods

### 2.1 Subjects

Two male subjects (33 and 61 years of age) with normal visual function served as observers for this investigation. Both are vision scientists and experienced observers. Each of subjects was given an opportunity to practice to become familiar with the experimental arrangement and testing paradigm and to become familiar with the psychophysical procedure.

### 2.2 Apparatus and Procedures

The stimulus display consisted of a rear projection system manufactured by Fakespace Systems[1] (Marshalltown, Iowa), which included a Christie Digital[2] 6000 lumen projector (Cypress, California) and three 10-foot-high by 12.5-foot-wide screens positioned in a "U" configuration, with the observer situated near the center of the display area (6.25 feet from both side screens and 11.25 feet from the front screen). The display resolution (for each screen) was 1600 x 1200 pixels, with each pixel subtending 4.3 minutes of arc at the nearest viewing area. Figure 1 shows the stimulus display system. The fixation target (depicted larger in the photograph than actually presented) was centered on the middle screen at eye level of a seated subject, and moving stimuli were projected onto the right screen. All three screens presented a uniform background

[1]Fakespace Systems is a registered trademark of Fakespace Systems, Inc.
[2]Christie Digital is a registered trademark of Christie Digital Systems, Inc.

luminance of 17 candelas per square meter ($cd/m^2$). The fixation target was a circular ring with variable gap locations and a thickness and diameter that correspond to approximately a 20/80 visual acuity. Sixteen combinations of four gaps in the ring (the gaps were up, down, right, and left) were presented at 0.5-second intervals. The subject was given a two-button mouse that served as his response interface for the two tasks. Initially, the two mouse buttons are pressed to synchronize the two computers controlling the targets on the front and right side screen. After 5 seconds, the fixation target was presented. The subject pressed the left mouse button when two horizontal slots or four slots appeared in the ring. The correct responses were recorded as part of the divided attention task. The fixation target was 4.3 times greater than the size of a 20/20 visual acuity letter in order to present supra-threshold, yet attention-demanding, targets. The moving targets were projected onto the right screen and consisted of a single black dot (12.9 $cd/m^2$) in one of three positions: 53.4, 72.6, and 90 degrees in the temporal visual field of the right eye, with the diameter of the dot subtending an angle of 5 degrees at the subject testing distance. One computer was used for each screen (front and right only) to generate and present targets via page-flip animation. Each computer used a 1-millisecond (ms) resolution timer, and these timers were synchronized with a simultaneous key board button press. The computers recorded all presentation events for both screens and translated those data into Excel[3] format.

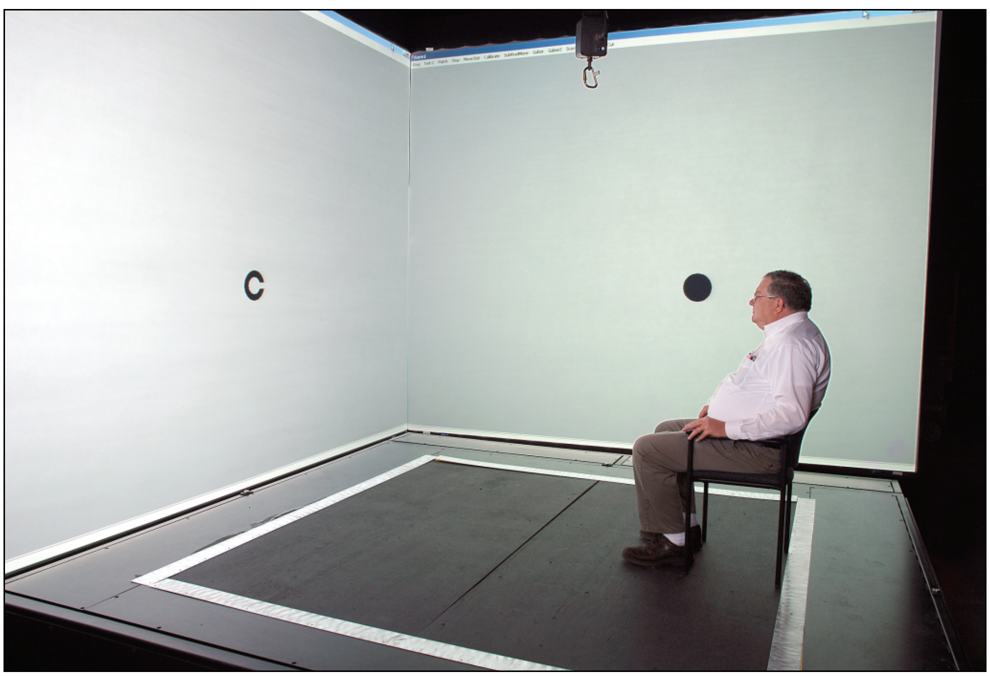

Figure 1. The stimulus display system.

We initiated stimulus trials by having the observer depress a mouse button. To maintain steady fixation on the central stimulus, the observer was required to discriminate two particular patterns of the 16 possible combinations of the four gaps in the fixation ring (up, down, left, and right). After

[3]Excel is a trademark of Microsoft Corporation.

each 500-ms presentation, the subject was given 1 second to respond, and all subject responses were recorded. If no response, no data were recorded. The recorded response times were compared with correct responses as an indication of the subjects' attentiveness to the fixation task. Two of 16 patterns were selected to increase the task difficulty. Two gap options were chosen, one where the slots were in opposition to make the target look like a horizontal flat-bladed screw; the other choice was all four gaps making the target look like a Phillips screw. The horizontal and Phillips patterns were presented at random, with an expectation of occurrence of approximately once every 4 seconds. The fixation target presentation provided a divided attention (central versus peripheral) component to the test procedure. Divided attention is a common occurrence for many real-world tasks required by the Soldier, such as surveillance, target detection and identification, visual search, and related activities. During each motion stimulus trial, only one of the three peripheral black dots was presented and once presented, remained stationary for 1 second and then was displaced by a variable distance toward the center of the display. The dot remained stationary again for 1 second before disappearing and the next black dot was presented. The travel distance of the dots was transformed to angular motion at the eye. This transformation compensated for the configuration of the display screens (departure from a hemispherical surface) where targets move between points on a path parallel to the line of sight. A non-hemispheric screen may influence target motion perception over a limited number of pixels. The target size, shape, and illumination may be influenced throughout the interval; however, the motion detection data derived in this pilot study were appropriate to address our hypothesis. The shape and size of peripheral targets is quite variable and is affected by many factors, but the perceived size of targets in the periphery would not affect the outcome of this study (*48*). Future studies will incorporate a software algorithm to compensate for non-hemispheric screen factors.

Motion thresholds that exceeded the 1-second detection interval were determined by means of a Bayesian forecasting strategy referred to as the "Best PEST" (Parameter Estimation by Sequential Testing) (*40*, *49*), which predicted the angular displacement needed to detect stimulus motion. Simultaneously with the presentation of the central fixation target, a moving target was presented on the right screen in the subject's extreme temporal visual field (the left visual field was not tested in this pilot study). The subject was asked to respond by pressing the right mouse button when he sensed movement of the peripheral target during the 1-second detection interval or within 1 second thereafter. These timed responses and presentations were recorded by a Delphi[4] compiled program and stored into an Excel spreadsheet file that permitted future data analysis and plotting. Three simultaneous PEST procedures, one for each of the peripheral dot locations and two stationary catch trials (to identify false positive responses), were run in random order. We established the initial starting point of the PEST by estimating the range of motion detection in previous test trials. Next, the logistic equation with standard deviation equal to one-fifth the range was assumed for the psychometric function. Likelihood functions for a "yes" and a "no" response to a test at a given threshold were derived from these data. The threshold measured was motion detection, not motion

[4]Delphi is a trademark of Borland Software Corporation.

direction, thereby allowing the use of a yes/no rather than forced choice procedure. We obtained a starting probability density function (p.d.f.) by assuming a yes response at maximum stimulus and a no response at the minimum stimulus. The choice of the mode or peak of the p.d.f. was then used to test the subject. Depending on the subject's response, the p.d.f. was revised by the appropriate likelihood function by means of Bayse's conditional probability theorem, namely, the subject had a given range of probabilities and responded in a particular way. After ten repetitions, the p.d.f. was narrowed to a sufficient extent that the 90% confidence interval could be verified to see if it met a pre-determined value. Also, this function could be converted to a cumulative distribution over possible thresholds to give the most recent revision of the psychometric function.

The 90-degree psychometric function estimate chosen in this pilot study was determined from research data that quantified thresholds from less eccentric retinal positions. The threshold approximation data used in the pilot study did not translate as expected and the resultant range chosen was not large enough to prevent a plateau of the data for the 90-degree target location. The historical retinal threshold data could not be used to accurately predict the psychometric function; it should have allowed for more than the 30-pixel total target movement used in this pilot study. The subjects reached the maximum displacement without going higher because of the limited motion threshold range selected. This pilot study, however, fortunately provided the data for a more appropriate 90-degree psychometric function estimate and motion threshold range for future research studies. The number and type of subject in this study were limited by its classification as a "pilot study" to determine proof of concept.

## 3. Results

Figure 2 presents psychometric functions for motion thresholds (angular displacement in degrees during the 1-second target motion interval) obtained at 53.4, 72.6, and 90 degrees in the temporal visual field of the first observer. The psychometric functions indicate that larger stimulus excursions were needed to detect motion at greater eccentricities, and the slope of the psychometric function became shallower, which suggests larger variability at higher stimulus eccentricities. Threshold was defined as the movement corresponding to the 50% probability of detection level. In accordance with previous investigations (*30*), motion thresholds increased at greater stimulus eccentricities, resulting in motion thresholds of approximately 0.55 deg/sec at 53.4 degrees' eccentricity, 1.15 deg/sec at 72.6 degrees' eccentricity, and 2.15 deg/sec at 90 degrees' eccentricity. Figure 3 represents the stimulus movement presented during the threshold estimation trials at each of the peripheral eccentricities. Individual symbols indicate individual probability of detection values for various stimulus movements, and the solid and dotted lines indicate the best psychometric fit to the data. Stable threshold levels are achieved in fewer than 10 trials, indicating that the test procedure is both accurate and efficient.

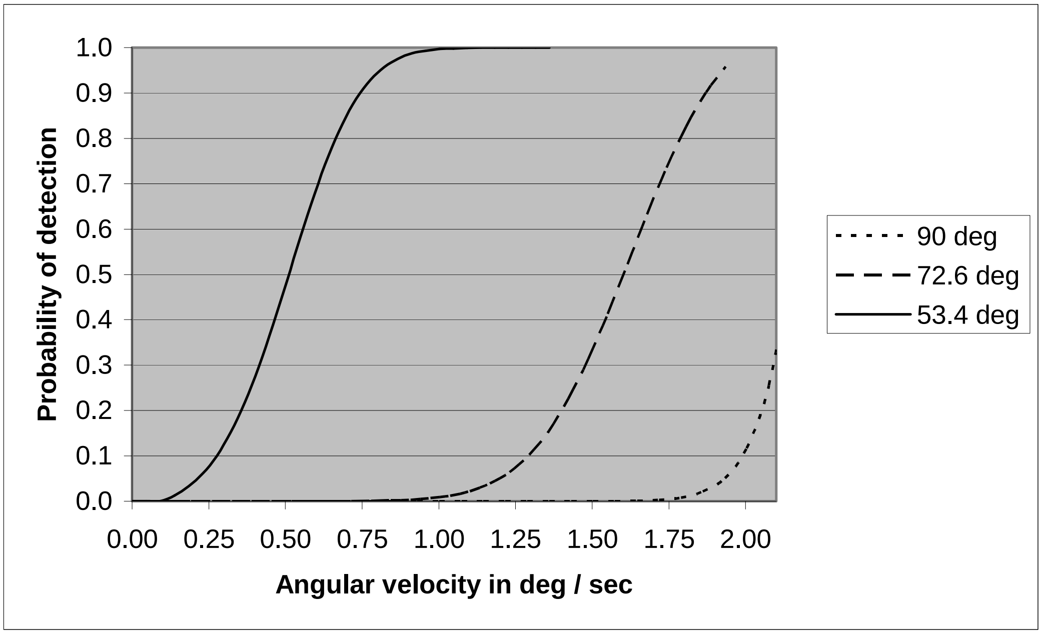


Figure 2. Psychometric functions for angular movement sensitivity (velocity in degrees per second) obtained at 53.4, 72.6, and 90 degrees in the temporal visual field (right eye) for subject 1in this experiment. (Motion threshold data were obtained with a PEST [Bayesian] threshold estimation procedure.)

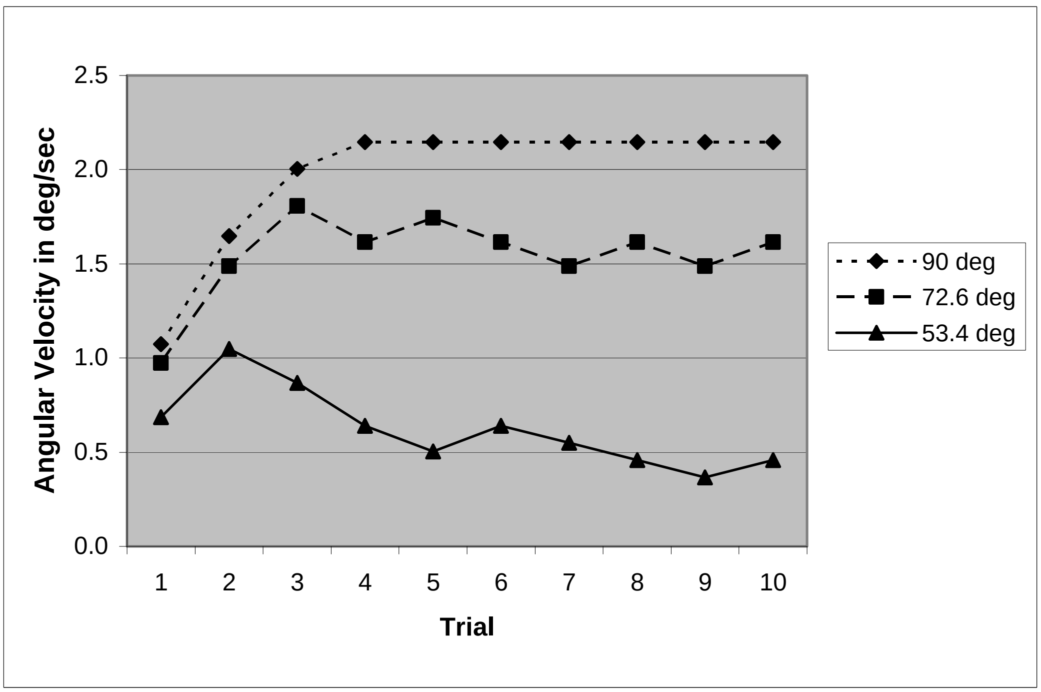


Figure 3. Raw data for individual PEST trials determined at 53.4, 72.6, and 90 degrees in the temporal visual field (right eye) for subject 1 in this experiment. (After each presentation, the PEST procedure refines the estimate of threshold angular velocities at each eccentricity until the final value [within a 90% confidence interval] is obtained.)

Figure 4 presents the psychometric functions for a second observer. The motion threshold at 53.4 degrees is approximately 0.45 deg/sec, which is slightly lower than that obtained for the first observer. The motion threshold at 72.6 degrees is 1.55 deg/sec, which is modestly higher than for the first observer, and the 90-degree threshold is approximately 2.15 deg/sec, which is similar to that obtained for the first observer. These modest motion threshold differences may be within the range of normal subject variability for sensitivity values of the extreme retinal periphery. The stimulus excursions for each stimulus trial (figure 5) again demonstrate that stable threshold estimates are obtained in a relatively short amount of time. Overall, the results for both observers are similar and reveal only modest increases in threshold estimations for greater eccentricities.

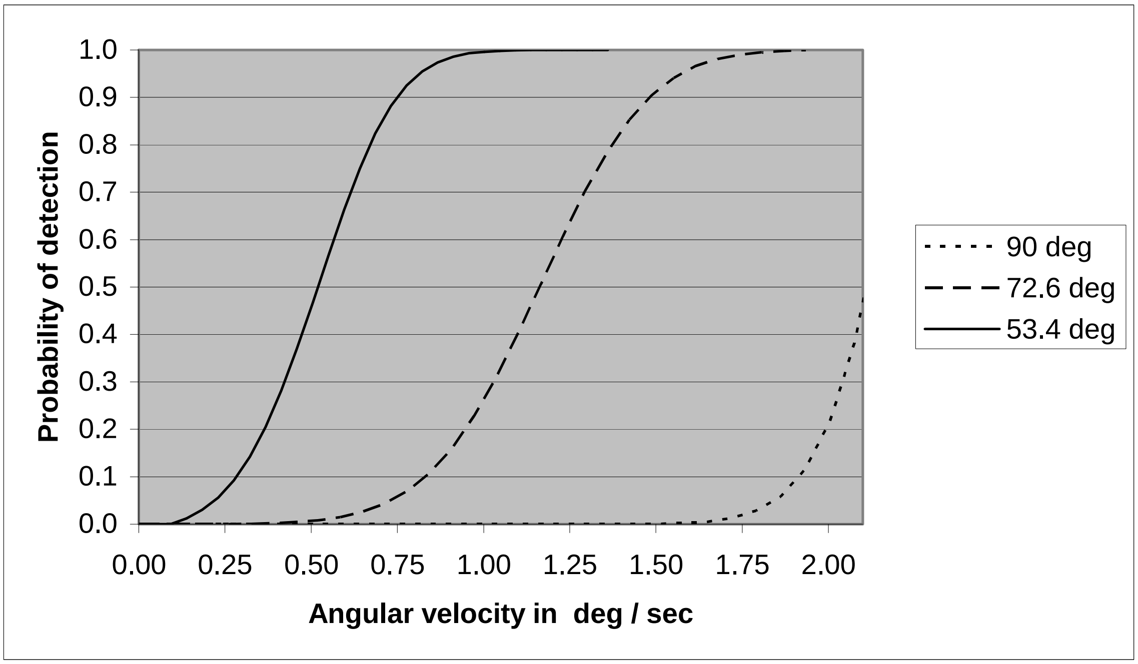


Figure 4. Psychometric functions for angular movement sensitivity (velocity in degrees per second) obtained at 53.4, 72.6, and 90 degrees in the temporal visual field of the right eye for subject 2 in this experiment. (Motion threshold data were obtained with a PEST threshold estimation procedure.)

Additional raw data are available in appendix A and demonstrate the consistency of each subject's tracking performance in subsequent trials.

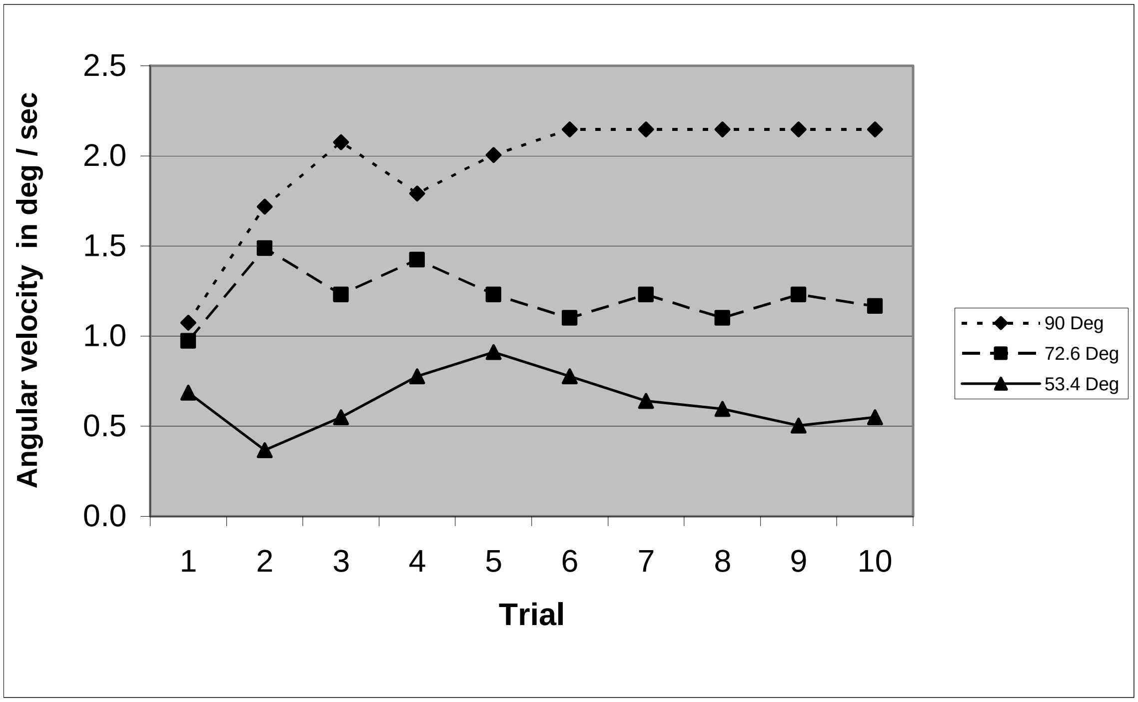


Figure 5. Raw data for individual PEST trials determined at 53.4, 72.6, and 90 degrees in the temporal visual field (right eye) for subject 2 in this experiment. (After each presentation, the PEST procedure refines the estimate of threshold angular velocities at each eccentricity until the final value [within a 90% confidence interval] is obtained.)

## 4. Discussion

The results obtained from this investigation provide strong evidence to support each of the three pilot study goals: First, it is clear that motion detection thresholds for the far peripheral visual field can be obtained with current computer and video technology. The stimulus characteristics employed for this study involve the use of a rather sophisticated display system that must coordinate and synchronize displays on three large projection screens, yet permit accurate and precise control of the dynamic stimuli that are displayed. The motion detection thresholds that were obtained for this investigation are similar to those that have been reported in previous studies with considerably different equipment (*12*, *30*).

Secondly, the use of a Bayesian forecasting test strategy instead of a method of adjustment, method of limits, or "staircase" procedure appears to be feasible for evaluating the far peripheral visual field as well. We are unaware of any previous studies that have applied such a threshold estimation methodology for determining performance characteristics in the far periphery. Our findings indicate that it is possible to apply Bayesian strategies in an accurate and efficient manner to obtain far peripheral motion thresholds and to take advantage of many other beneficial aspects (higher reproducibility and reliability, etc.) of these techniques for examining the far peripheral visual field. Our findings indicate that it should be possible to obtain reliable thresholds within 10 stimulus presentations, and further refinement of these procedures could enhance the accuracy and efficiency of these procedures.

Finally, these results indicate that it is possible to evaluate the importance of motion sensitivity as a component of task performance in many real-world situations. With this display system, it is possible to measure motion sensitivity and compare it to task performance for visual search, object detection and identification, and related tasks that can be implemented via the same display system. Alternatively, a multitasking situation (common for many real-world tasks) could be initiated on the display system, where motion detection is but one of several tasks to perform. In addition, the introduction of a dynamic self-motion component could be added to the test regimen by the introduction of a two-dimensional treadmill to simulate real-world mobility tasks. In this type of system, it is possible to initiate a myriad of simulation conditions to examine the importance of viewing during degraded visibility (darkness, fog, low contrast, blur), multitasking and attentional issues, and visuomotor coordination. We are currently in the process of implementing and refining such procedures for future research efforts.

The recent literature reports of different anatomical and physiological processing of visual information for the far temporal visual field also introduces a number of interesting questions (*39*). Are there differences in the salience of various stimulus parameters for this portion of the visual field? What purposes do these altered processing methods serve the individual in terms of interaction with the environment? What is the importance of this region for locomotion and other mobility tasks (*45*, *46*)? Our findings indicate that it is possible to obtain motion detection (displacement) thresholds in the far peripheral visual field with the use of Bayesian threshold estimation procedures. With the experimental paradigm outlined in this investigation, we believe that insights into many of these issues can be successfully achieved.

## 5. References


1. Lott, L. A.; Haegerstrom-Portnoy, G.; Schneck, M. E.; Brabyn, J. A. Face recognition in the elderly. *Optom Vis Sci* **2005**, *82*, 874–881.
2. Brooks, B. E.; Cooper, E. E. What types of visual recognition tasks are mediated by the neural subsystem that subserves face recognition? *J Exp Psychol Learn Mem Cogn* **2006**, *32*, 684–698.
3. Legge, G. E.; Glenn, A. Fry Award Lecture 1990: three perspectives on low vision reading. *Optom Vis Sci* **1991**, *68*, 763–769.
4. Akutsu, H.; Legge, G. E.; Ross, J. A.; Schuebel, K. J. Psychophysics of reading – X. Effects of age-related changes in vision. *J Gerontol* **1991**, *46*, 325–331.
5. Anderson, D. R.; Patella, V. M. *Automated Static Perimetry*. St. Louis; CV Mosby, 1999.
6. Aulhorn, E.; Harms, H. *Visual Perimetry. In Handbook of Sensory Physiology; Vol VII/4 Visual Psychophysics*, (Jameson and Hurvich, eds), Berlin: Springer-Verlag, 1972; 102–145.
7. Johnson, C. A.; Keltner, J. L.; Balestrery, F. G. Acuity profile perimetry. Description of technique and preliminary clinical trials. *Archives of Ophthalmology* **1979**, *97*, 684–689.
8. Johnson, C. A.; Keltner, J. L.; Balestrery, F. G. Static and acuity profile perimetry at various adaptation levels. *Documenta Ophthalmologica* **1981**, *50*, 371–388.
9. Demer, J. L. Evaluation of vestibular and visual osculomotor function. *Otolaryngol Head Neck Surg* **1995**, *112*, 16–35.
10. Guedry, F. E.; Lentz, J. M.; Jell, R. M. Visual-vestibular interactions: I. Influence of peripheral vision on suppression of the vestibulo-ocular reflex and visual acuity. *Aviat Space Environ Med* **1979**, *50*, 205–211.
11. McKendrick, A. M.; Badcock, D. R.; Morgan, W. H. The detection of both global motion and global form in glaucoma. *Invest Ophthalmol Vis Sci* **2005**, *46*, 3693–3701.
12. Ruben, S.; Fitzke, F. Correlation of peripheral displacement thresholds and optic disc parameters in ocular hypertension. *Br J Ophthalmol* **1994**, *78*, 291–294.
13. Thibos, L. N. Acuity perimetry and the sampling theory of visual resolution. *Optom Vis Sci* **1998**, *75*, 399–406.
14. Verdon-Roe, G. M.; Westcott, M. C.; Viswanathan, A. C.; Fitzke, F. W.; Garway-Heath, D. F. Exploration of the psychophysics of a motion displacement hyperacuity stimulus. *Invest Ophthalmol Vis Sci* **2006**, *47*, 4847–4855.

15. Wall, M.; Jennisch, C. S. Random dot motion stimuli are more sensitive than light stimuli for detection of visual field loss in ocular hypertension patients. *Optom Vis Sci* **1999**, *76*, 550–557.

16. Wall, M.; Jennisch, C. S.; Munden, P. M. Motion perimetry identifies nerve fiber bundlelike defects in ocular hypertension. *Arch Ophthalmol* **1997**, *115*, 26–33.

17. Wall, M.; Montgomery, E. B. Using motion perimetry to detect visual field defects in patients with idiopathic intracranial hypertension: a comparison with conventional automated perimetry. *Neurology* **1995**, *45*, 1169-1175.

18. Bedell, H. E.; Johnson, C. A. The effect of flicker on foveal and peripheral thresholds for oscillatory motion. *Vision Res* **1995**, *35*, 2179–2189.

19. Finlay D. Motion perception in the peripheral visual field. *Perception* **1982**, *11*, 457–462.

20. Foster, D. H.; Gravano, S.; Tomoszek, A. Acuity for fine-grain motion and for two-dot spacing as a function of retinal eccentricity: Differences in specialization of the central and peripheral retina. *Vision Res* **1989**, *29*, 1017–1031.

21. Johnson, C. A. Leibowitz H. W. Practice, refractive error, and feedback as factors influencing peripheral motion thresholds. *Perception and Psychophysics* **1974**, *15*, 276-280.

22. Johnson, C. A.; Leibowitz, H. W. Velocity-time reciprocity in the perception of motion: foveal and peripheral determinations. *Vision Res* **1976**, *16*, 177–180.

23. Johnson, C. A.; Scobey, R. P. Foveal and peripheral displacement thresholds as a function of stimulus luminance, line length and duration of movement. *Vision Res* **1980**, *20*, 709–715.

24. Johnson, C. A.; Scobey R. P. Effects of reference lines on displacement thresholds at various durations of movement. *Vision Res* **1982**, *22*, 819–821.

25. Post, R. B.; Johnson, C. A. Motion sensitivity in central and peripheral vision. *Am J Optom Physiol Opt* **1986**; *63*: 104–107.

26. Post, R.B.; Scobey, R.P.; Johnson, C.A. Effects of retinal eccentricity on displacement thresholds for unidirectional and oscillatory stimuli. *Vision Res* **1984**, *24*, 835–839.

27. Scobey, R.P.; Johnson, C.A. Psychophysical properties of displacement thresholds for moving targets. *Acta Psychol* **1981**, *48*, 49–55.

28. Scobey, R.P.; Johnson, C. A. Displacement thresholds for unidirectional and oscillatory movement. *Vision Res* **1981**, *21*, 1297–1302.

29. Wesemann, W.; Norcia, A. M. Contrast dependence of the oscillatory motion threshold across the visual field. *J Opt Soc Am A* **1992**, *9*, 1663–1671.

30. Leibowitz, H. W.; Johnson, C. A.; Isabelle, E. Peripheral motion detection and refractive error. *Science* **1972**, *177* 1207–1208.

31. Koenderink, J. J.; van Doorn, A. J.; van de Grind, W. A. Spatial and temporal parameters of motion detection in the peripheral visual field. *J Opt Soc Am A* **1985**, *2*, 252–259.

32. Koenderink, J. J.; Bouman, M. A.; Bueno de Mesquita, A. E.; Slappendel, S. Perimetry of contrast detection thresholds of moving spatial sine wave patterns. I. The near peripheral visual field (eccentricity 0o-8 o). *J Opt Soc Am* **1978**, *68*, 845–849.

33. Koenderink, J. J.; Bouman, M. A.; Bueno de Mesquita, A.E.; Slappendel, S. Perimetry of contrast detection thresholds of moving spatial sine wave patterns. II. The far peripheral visual field (eccentricity 0o-50 o). *J Opt Soc Am* **1978**, *68*, 850–854.

34. Koenderink, J. J.; Bouman, M. A.; Bueno de Mesquita, A.E.; Slappendel, S. Perimetry of contrast detection thresholds of moving spatial sine wave patterns. IV. The influence of the mean retinal illuminance. *J Opt Soc Am* **1978**, *68*, 860–865.

35. Koenderink, J. J.; Bouman, M. A.; Bueno de Mesquita, A. E.; Slappendel, S. Perimetry of contrast detection thresholds of moving spatial sine wave patterns. I. The near peripheral visual field (eccentricity 0o-8 o). *J Opt Soc Am* **1978**, *68*, 845–849.

36. Leibowitz, H. W. The relation between the rate threshold for the perception of movement and luminance for various durations of exposure. *J Exp. Psychol* **1955**, *49*, 209–214.

37. McKee SP, Nakayama K. The detection of motion in the peripheral visual field. *Vision Res* **1984**; *24*: 25–32.

38. Beard, B. L.; Klein, S. A.; Carney, T. Motion thresholds can be predicted from contrast discrimination. *J Opt Soc Am A* **1997**, *14*, 2449–2470.

39. Palmer, S. M.; Rosa, M.G.P. A distinct anatomical network of cortical areas for analysis of motion in far peripheral vision. *European Journal of Neuroscience* **2006**, *24*, 2389–2405.

40. Pentland, A. P. Maximum likelihood estimation: the best PEST. *Percept Psychophys* **1980**, *28*, 377–379

41. Watson, A. B.; Pelli, D. G. QUEST: A Bayesian adaptive psychometric method. *Percept Psychophys* **1983**, *33*, 113–120.

42. Bengtsson, B.; Olsson, J.; Heijl, A.; Rootzen H. A new generation of algorithms for computerized threshold perimetry, SITA. *Acta Ophthalmol* **1997**, *75*, 368-375.

43. Turpin, A.; McKendrick, A. M.; Johnson, C. A.; Vingrys, A. J. Properties of perimetric threshold estimates from Full Threshold, ZEST and SITA-like strategies as determined by computer simulation. *Investigative Ophthalmology and Visual Science* **2003**, *44*, 4787–4795.

44. Anderson, A. J.; Johnson, C. A. Comparison of the ASA, MOBS and ZEST threshold methods. *Vision Research* **2006** *46*, 2403–2411.

45, Kochhar, D. S.; Fraser, T. M. Monocular peripheral vision as a factor in flight safety aviation. *Space, and Environmental Medicine* **1978**, 698–706.

46. Johansson, G. Studies on visual perception of locomotion Perception. **1977**, *6*, 365–376.

47. Shabana, N.; Peresm V, C,; Carkeet, A; Chew, P.T.K. Motion perception in glaucoma patients: A review. *Survey of Ophthalmology* **2003**, *48*, 92–106.

48. Bedell, H. E.; Johnson, C. A. The perceived size of targets in the peripheral and central visual fields. *Opththalmic and Physiological Optics* **1984**, *4*, 123–131.

49. Lieberman, H. R.; Pentland, A. P. Microcomputer-based estimation of psychophysical thresholds: The Best PEST. *Behavior Research Methods & Instrumentation* **1982**, *14* (1), 21–25.

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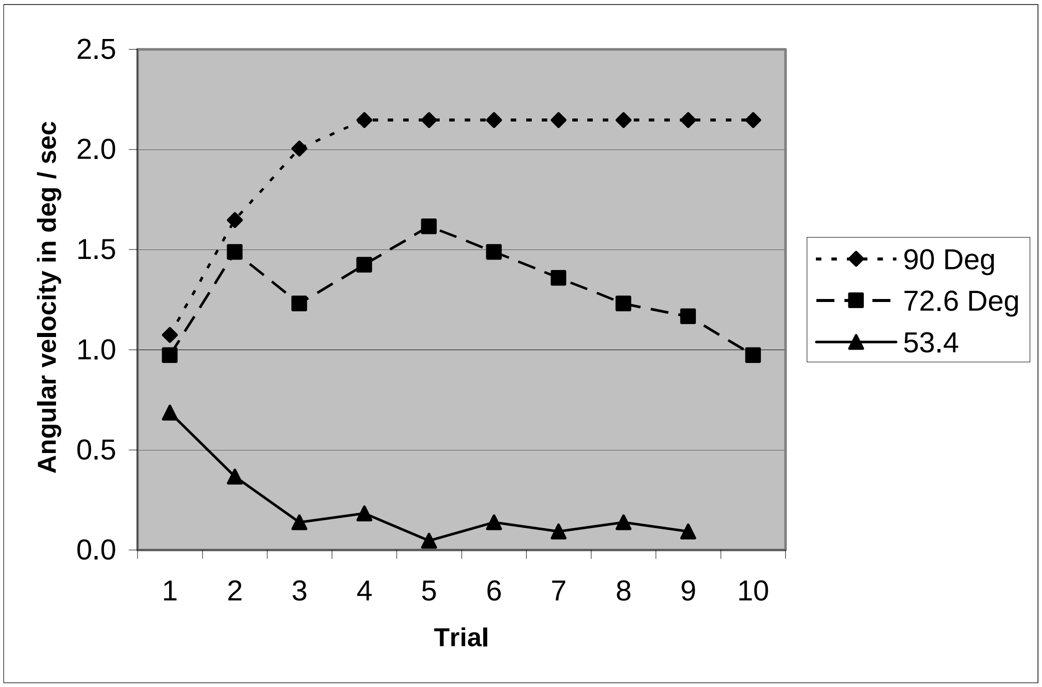
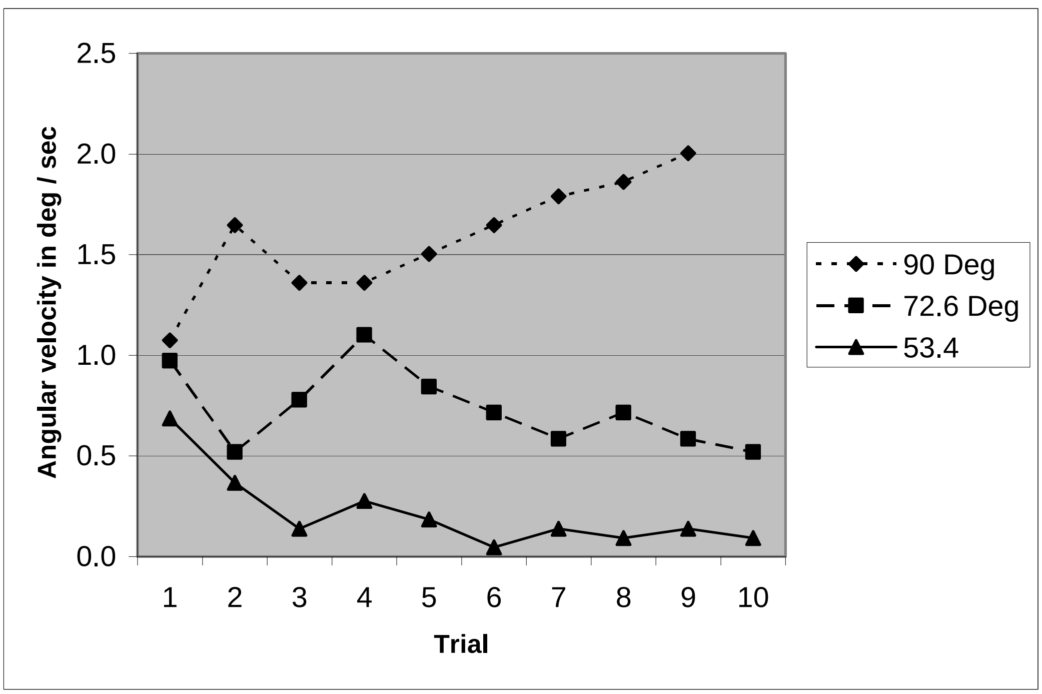
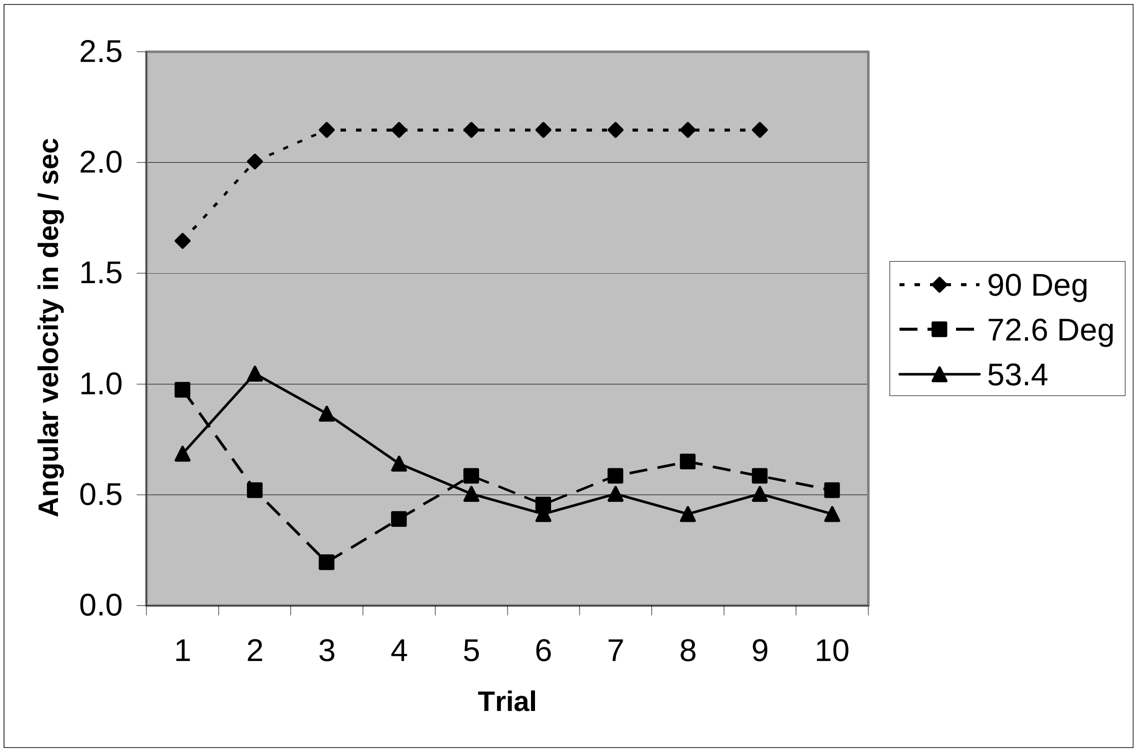
## Appendix A. Additional Raw Data for Subjects 1 and 2

These data are included for completeness.




Detection of Target Angular Velocity - PEST Procedure Estimates by Trial for Three Eccentricities (Subject 2)



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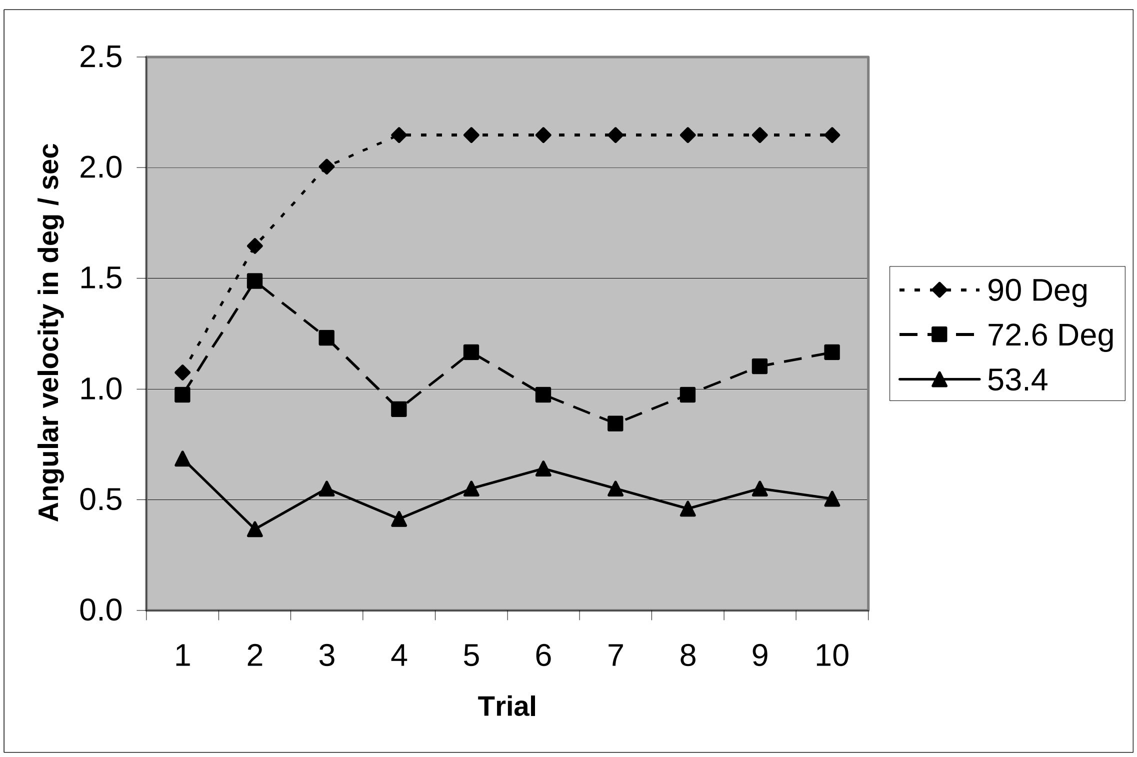

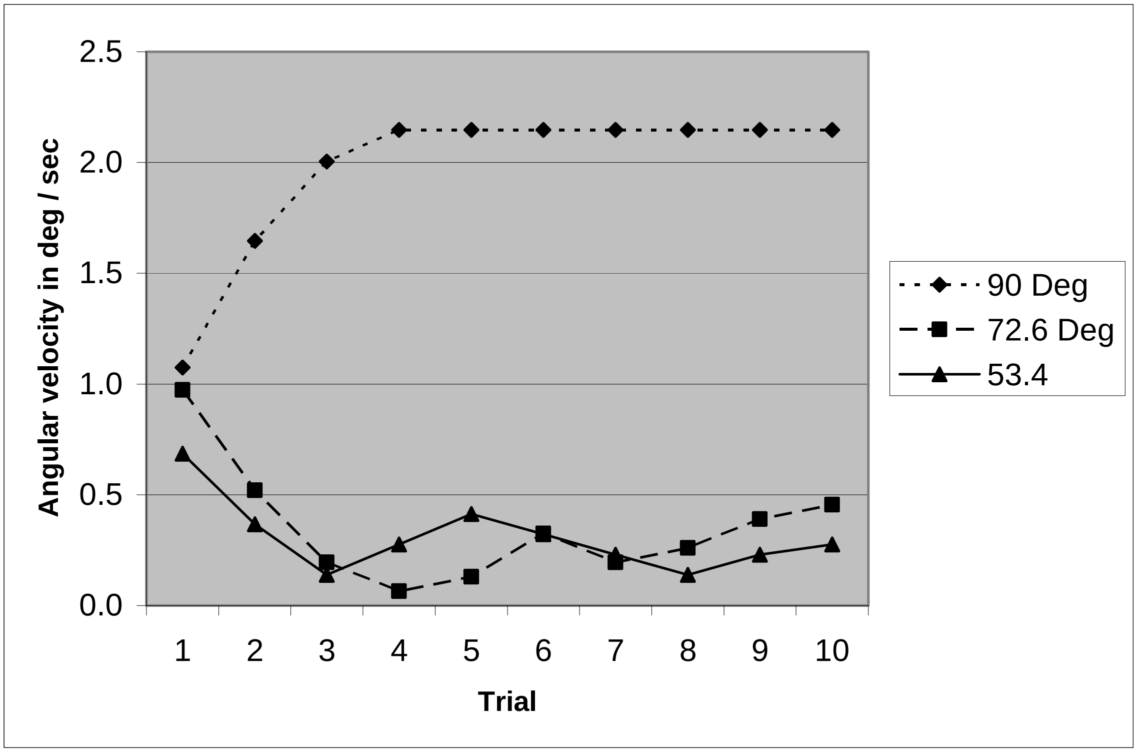


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